

IDENTIFYING TEMPORAL AND SPATIAL VARIABILITY OF GROUNDWATER DISCHARGE USING A DISTRIBUTED TEMPERATURE SENSING (DTS) SYSTEM WITHIN THE LOWER REACHES OF THE RIVER HUN, NORTH-WEST NORFOLK.

by

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accordance with the regulations of the University of East Anglia

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Abstract

A distributed temperature sensing (DTS) system is utilised in an environmental study of the lower reaches of the River Hun in North-West Norfolk. The essential component of the DTS system is a fibre-optic cable, emplaced along the river bed in a predetermined 'test' section of the river. The main objective of the study was to identify groundwater discharge zones through the River bed. Groundwater temperatures are more stable, and are expected to be significantly different to the surface water during the field study timeframe (30/04/2010 to 13/05/2010) enabling visual identification of anomalies through graphical representations of the temperature readings. The DTS system provided an extremely rich data set allowing spatial and temporal data analysis of lateral temperature data. The analysis found several temperature anomalies throughout the test section but these were not considered to be representative of groundwater inflow. Several surface water bodies were found to spatially correlate with the temperature anomalies, one of which was further investigated with spot temperature probing which subsequently suggested a natural linkage with the adjacent River Hun. Temperature increases up to 350 m upstream of the River mouth were also identified by the DTS, these were found to temporally correlate with the spring high tide cycle. No definitive groundwater inflows were identified by data analysis. This is considered to be due to either minimal, or lack of, groundwater inflow or poor emplacement of the fibre optic cable which caused excessive variability in the dataset. Recommendations are made for improvements to follow-up studies to subsequently enable identification of groundwater inflows.

Keywords: Distributed temperature sensing; Environmental monitoring; Hydrology; River system dynamics

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1. INTRODUCTION

1.1 Background

Groundwater and surface water systems can be hydraulically connected, understanding of interactions between these systems is essential to effective resource management. The transition zone between groundwater and surface water is known as the hyporheic zone. Through this zone, transport, degradation, transformation, precipitation, and sorption of substances can occur which has a profound effect upon water quality (Kalbus *et al.*, 2006). Additionally, it is ecologically important for both aquatic and benthic organisms, the proliferation of which can affect the ecological classification of a water body and subsequently the anthropogenic use of the resource. Thus, a consideration of the groundwater-surface water interaction is a necessity for hydrological studies.

Identification and quantification of water fluxes in a groundwater-surface water system has traditionally been carried out via direct measurements from seepage meters or estimations of Darcian flux using piezometers and hydraulic conductivity (K) values. Limitations in both techniques have been identified by Murdoch and Kelly (2003), who found that external flow over the collection bag of the seepage meter caused artificial increases in recorded measurements. They also found that the internal design of the seepage meter caused an increase in flow resistance. Surridge *et al.* (2005) found that methodological technique related issues arise too easily through emplacement of piezometers in compressible soils. In particular, forceful emplacement of piezometers was found to cause compaction and general disturbance of *in-situ* soils rendering the slug test ineffective.

Where groundwater is found to discharge to a river it is termed 'gaining', conversely where no discharge is identified in the river it is termed 'losing'. This may apply to a river as a whole or to differing sections of the surface water body. In relation to the DTS system temperature variations along the length of the field study test section of the River Hun are expected to be relatively small and constant where groundwater discharge is predominantly diffuse. However, if focused or discrete groundwater discharge predominates, more abrupt changes in temperature are expected to be identified.

1.2 Aims and Objectives

The primary objective of the study was the identification of groundwater discharge into the River Hun by utilisation of the DTS system method. Secondary objectives included identification of temporal and spatial variability of discharges and differentiation of discrete

and diffuse discharges. Completion of these objectives should prove the effectiveness of the DTS system at identifying groundwater discharge and consequently provide additional support for the use of this modern technique as a tool for practicing hydrologists or environmental scientists/engineers/technicians.

The outcomes of the project will provide greater understanding of groundwater-surface water interactions in the lower reaches of the River Hun. In addition, the data obtained may provide the basis for further research into quantifying groundwater discharge in this section of river. This will require further fieldwork to ascertain river discharge rates over the test section and application of thermal energy balance theory. The field study will also provide the opportunity to test the accuracy of the DTS system and see if the system has the capability to identify physical processes such as groundwater discharge into lowland rivers of this nature and test the methodology for emplacement of the fibre optic cable which can be logistically challenging.

1.3 Recent Studies using DTS

Selker *et al.* (2006b) present one of the earliest hydrological studies utilising fibre optic DTS system technology. The study investigated the Maisbach, a first order stream in Luxembourg, with the aim of displaying the new method's capabilities by identifying gaining or losing sections of the stream. The fibre optic cable was placed along the stream bed and held in place by stones to prevent it being dislodged by bed load, animals or other detrital material transported by the stream. Along with the DTS dataset, stream gauging was also utilised to enable quantification of groundwater inflows using thermal energy balance theory. The subsequent analysis identified abrupt temperature increases, attributed to groundwater inflow within a gaining section of the River, and gradual decreases considered to be representative of losing sections. Closer inspection the groundwater inflows were found to correlate with aquifer exposures in the stream which were identified through a detailed inspection of the stream bed. The current study aims to identify similar increases in temperature as to those identified by Selker *et al.* (2006b). Westhoff *et al.* (2007) present a study of the same DTS data from the Maisbach. The study presents a model integrating the environmental components of the hydrological system in order to quantify groundwater discharges within the River channel by using energy balance theory. The model calculates the total energy of the system incorporating solar radiation (including shading effects), longwave radiation, sensible heat flux, latent heat flux and river bed conduction. Groundwater inflows into the system

play a crucial role in producing an accurate model, consequently identifying temperature distributions through use of DTS play an equally important role. Lowry *et al.* (2007) carried out a study of a wetland stream complex, once more utilising a DTS system. The aim was to characterise spatial and temporal variations in groundwater inflow through ‘soil pipes’ contained in the underlying peat strata which were thought to control the groundwater-surface water interactions within the complex. The groundwater temperature was known to be in the region of 6-7 °C and surface water temperature ~17 °C and as they provide a focused discharge point, the ‘soil pipes’ caused strong reductions (up to ~6 °C) in temperature measurements and were easily identifiable by the DTS. Vogt *et al.* (2010) examine the potential for high resolution vertical temperature measurements by wrapping the fibre optic cable around a PVC tube to enable a much higher spatial resolution of approximately 5 mm. This allows a much more accurate estimation of groundwater discharge or surface infiltration in gaining or losing streams, respectively. Tyler *et al.* (2009) compare several DTS systems to determine the accuracy of manufacturer’s claims on spatial and temporal resolution, with particular attention paid to differences in set-up, calibration, configuration and combinations of different instruments.

1.4 Temperature as a Tracer

Temporal and spatial variations in groundwater discharge through the hyporheic zone can be difficult to identify due to the heterogeneous nature of the aquifer-surface water interaction. Temporal fluctuations can be caused by asynchronous water-table fluctuations between the stream and aquifer (Wroblicky *et al.*, 1998) or simply due to diurnal fluctuations in solar radiation and atmospheric temperature (including longwave radiation reflected back from the atmosphere)) (Selker *et al.*, 2006b). Spatial variability may be caused by heterogeneous hydraulic conductivity of streambed sediments (Kalbus *et al.*, 2009), river morphology and stream curvature (Cardenas *et al.*, 2004), and by spatially varying hydraulic gradients. Vogt *et al.* (2010) suggest that ‘clogging layers’ can form during times of low flow. These are accumulations of finer grained sediments which are deposited within the pore spaces of larger grains which form the stream bed, subsequently reducing hydraulic conductivity (Rehg *et al.*, 2005). Deposition of finer sediment in lower energy environments, e.g. inside of a meander, within more vegetated areas etc. may lead to preferential formation of springs. Temperature can be used as an environmental tracer for the aforementioned processes and the DTS system method is the most suitable for highlighting spatial and temporal variations.

Annual variance in groundwater temperatures is generally considered to be relatively low throughout the year. In contrast to this low variance, surface water temperatures exhibit high variance on both daily and seasonal timescales. Therefore, gaining reaches are characterized by relatively stable river bed temperatures and damped diurnal variations in surface water temperatures, whereas losing reaches are characterized by highly variable sediment and surface water temperatures (Winter *et al.*, 1998). This permits an identification of the general character of the flow regime by recording temperature time series in the stream and the surrounding sediments (Constantz, 1998; Constantz and Stonestrom, 2003).

As discussed previously, groundwater has a relatively stable temperature ‘signature’ in comparison with surface waters which are more variable due to external effects. This relatively stable groundwater temperature ‘signature’ is usually cooler than surface waters in the summer and warmer in the winter due to differences in atmospheric temperature and solar radiation. River temperatures, monitored by the DTS, should show greater variance in zones of localised/discrete discharge than in areas with little, diffuse or no groundwater discharge. Inference of groundwater discharge is most reliable when the difference between surface water and groundwater temperatures is at a maximum.

It should be noted that the actual temperatures recorded by the DTS system are of less importance than the relative temperature anomalies which are to be identified during the data analysis.

1.5 Principles of the DTS system

Distributed temperature sensing systems use a fibre-optic cable to carry a pulse of light with a specific frequency and wavelength. As the light encounters matter it is reflected back at three different frequencies, one the same as the original, one just above the original (Anti-Stokes backscatter) and one just below that of the original frequency (Stokes backscatter) (Figure 1). The frequency shifted signal is known as Raman Scattering. Below a certain light intensity the magnitude of scattering is a linear function of the intensity of illumination, while at these intensities the Anti-Stokes scattering is a function of the intensity of illumination and exponentially of the temperature of the fibre. Therefore, the ratio of the magnitudes of the Anti-Stokes to Stokes scattered light eliminates the intensity dependence and provides a quantity that depends exponentially on the fibre temperature (Selker *et al.*, 2006a). The temperature measured by the DTS system is an averaged value over 1 m lengths of fibre.

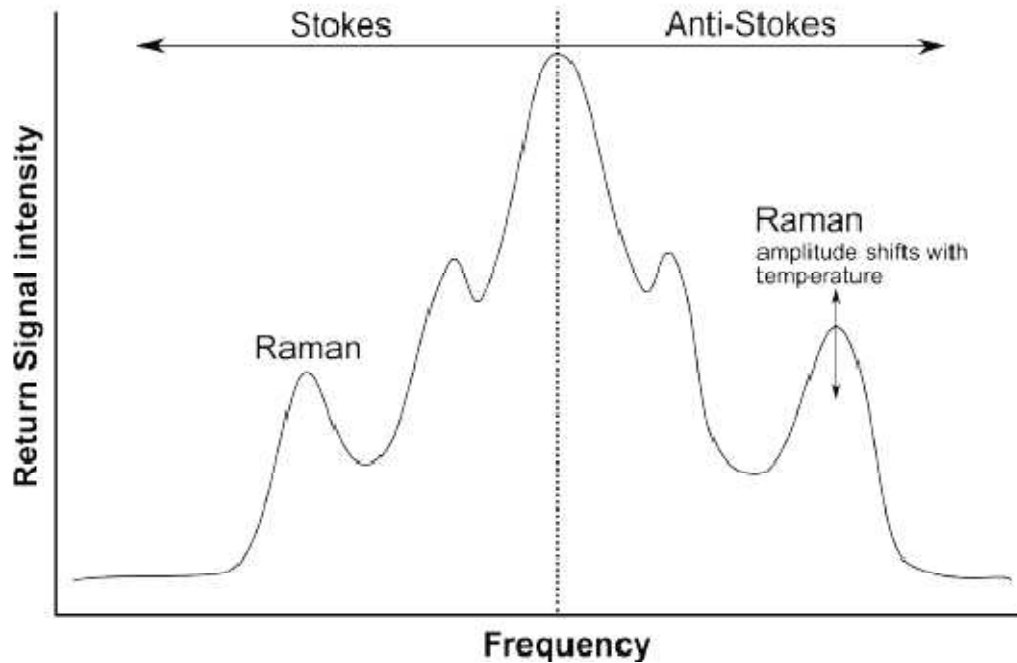


Figure 1 - Diagram of Raman Stokes Scattering (after Selker *et al.*, 2006a)

Using the DTS system, temperature distributions along 30,000 m long cables can be efficiently measured to 0.01 °C with a spatial accuracy of 1 m (Selker *et al.*, 2006a and 2006b), this method far surpasses any other current methodology for spatial and temporal temperature measurements of stream beds. For example, this study investigates a section of the River Hun approximately 2 km long, to obtain the same spatial and temporal resolution as the DTS system a traditional sensor array would require thousands of sensors and would be impractical and far more time consuming.

The advantage of the DTS system over traditional point measurement techniques, such as those described above, is the large amount of concurrent spatial data it can collect and the close control of variation in temporal data collection. Additionally, once emplaced, the system is exceptionally easy to use and relatively low maintenance. Thus, the DTS systems ability to retrieve an incomparable data set, potentially allowing identification of both discrete and diffuse groundwater discharge through the hyporheic zone can provide a greater understanding of spatial and temporal variability. This might be particularly useful where protection of the surface water resource from contamination by groundwater is a priority.

1.6 Site Description

The River Hun originates in Hunstanton Park, North West Norfolk. The River runs in a northerly direction before following the curvature of the coastline towards Holme-Next-The-Sea where the River discharges into the North Sea, the river mouth is surrounded by salt marshes and controlled by a sluice gate which controls tidal incursion (Figure 2) (Plates 1a and 1b). For the latter ~2 km the River is very straight as the river channel has been anthropogenically altered for agricultural purposes, providing the ideal location to emplace the DTS system. This part of the River is surrounded by Holme Dunes National Nature Reserve which is managed by the Norfolk Wildlife Trust and is designated a Site of Special Scientific Interest (SSSI) due to the importance the area plays as a habitat for many migratory birds. The reserve comprises a coastal dune system, a small woodland area, a lake (Broad Water), salt marshes and a large tract of pastoral farming land, such localised diversity of habitats is the reason for the importance of the National Nature Reserve. The agricultural land is considered to have been anthropogenically created as several drainage ditches can be found to bisect the pastoral fields and discharge into the River Hun. This area of agricultural land is expected to have originally been salt marshes, however it is not known when the drains were created, nor is it of significance to the study. The River itself was found to be in the region of 3-4 m in width and with variable depth, but generally increasing downstream from approximately 1 m to 3 m, in the centre of the channel, and along the 'test' section under study. In places the River was found to be overgrown with reeds which had channeled the flow into the centre of the river causing the river to temporarily hasten, deepen and narrow. A brief inspection of the river bed, conducted during emplacement of the fibre optic cable, found it to be composed of silts overlying sands with interspersed fine gravels, deposits which are typical of lowland rivers. Nearer the River banks silts and clays were dominant and are considered to be representative of the underlying geology of Holocene Salt Marsh Deposits.



Figure 2 – Aerial photo of Holme Dune Nature Reserve and River Hun test section (red)



Photographs 1a and 1b – Base station end of test section, overlooking (to the west) sluice gate (1a) and salt marshes to the east (1b). Photographs taken during the site walkover carried out on 12/03/10.

1.7 Regional Geology

The majority of Norfolk lies upon a raised plateau of Chalk which was formed during the cretaceous. This plateau subsides approaching the northerly coast where the Chalk has been proven to exhibit an East-West trending, synformal or valley type structure considered to be associated with regional tectonics (Chroston *et al.*, 1999). This basinal structure has been infilled with Pleistocene deposits of Glacial Sands and Gravels overlain by Glacial Till which diminishes seaward to be replaced with back-barrier Holocene Marsh deposits and subsequent modern dune and beach sands (Figure 3). Hydrogeologically, the Till acts as locally confining unit to the Chalk inland, where the majority of the recharge occurs, as such groundwater flow paths are expected to emerge within the marsh environment at the coast due to the lower hydraulic head and lower permeability of the formation (Figure 3). This

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conceptual model has already been proven by the identification of springs in North Norfolk marshes at Thornham, Stiffkey and Salthouse among others, (Green, 2004). It should be noted that the geological setting as described above has only been assumed for the site and may not be fully representative of the actual ground conditions. The cross-section depicted in Figure 3 represents a conceptual geological cross section of the field study area. This section was developed after the findings of Green (2004).

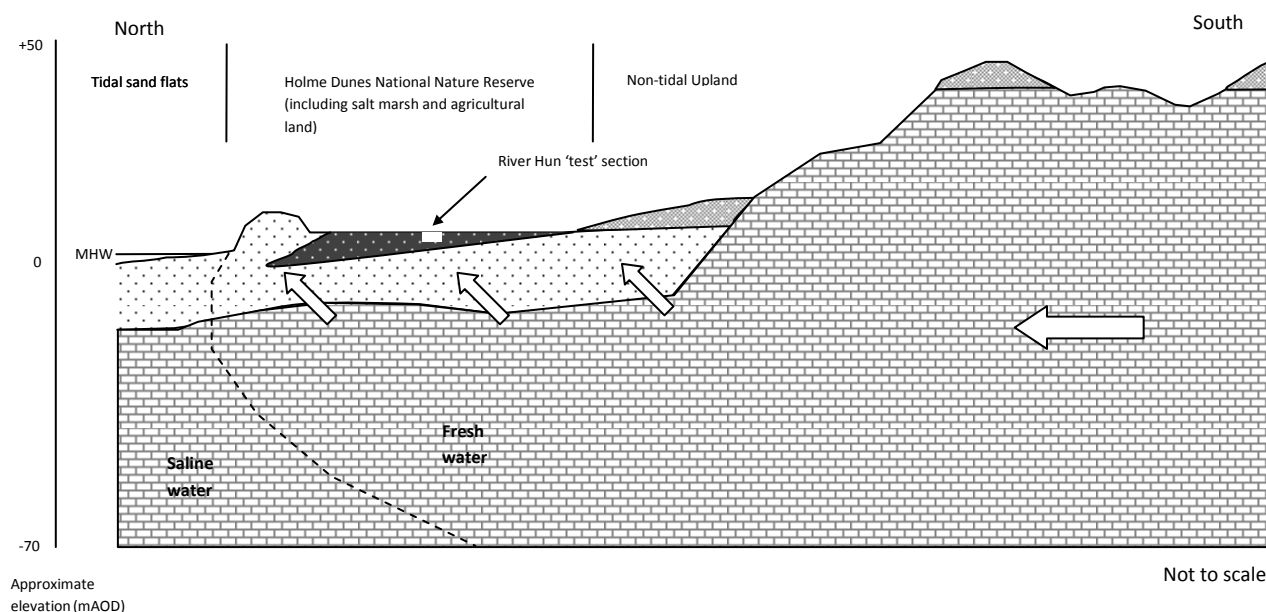
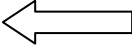
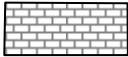


Figure 3 – Conceptual Geological Cross-section of field study site (after Green, 2004)

Key:-

-  **Groundwater flow direction**
-  **Holocene saltmarsh deposits**
-  **Pre-Holocene Holkham Till**
-  **Quaternary sand and gravel**
-  **Cretaceous Chalk**

2. FIELDWORK AND METHODS

2.1 Oryx Distributed Temperature Sensing System

To study possible groundwater inflows it was decided to use temperature as an environmental tracer, as described in section 1.4. The most current and efficient method for measuring temporal and spatial variance in temperature in a river is the DTS system method (Westhoff *et al.*, 2007, Tyler *et al.*, 2009, Vogt *et al.*, 2010). The field study utilised an Oryx DTS system manufactured by Sensornet and capable of detecting 0.01°C changes in temperature. The Oryx is a class 3B laser and data logging device, which can be connected to a laptop and programmed to measure at a desired spatial and temporal resolution for a specified duration and only being limited by the finite memory and/or the power supply. The fibre optic cable used was just over 2000 metres in length and consisted of four fibres, housed within both a steel and waterproof outer casing and marked at metre intervals, the majority of this was emplaced in the River with a small amount remaining at either end of the test section for use during calibration. Data retrieval by the Oryx DTS system can be configured for either a single or double ended measurement. The single ended measurement is made using light travelling in one direction in the fibre, or alternatively the double ended measurement is made by combining the data from a looped single ended measurement, where the cable is connected to the instrument at both ends. The temperature is derived from the backscatter of light signals which have travelled in opposite directions, as discussed in section 1.5. A double ended measurement is advantageous over a single ended measurement in many applications, as temperature-slope effects, the result of differential attenuation of the signal in the fibre, are automatically accounted for (Tyler *et al.*, 2009).

2.2 Site Walkover

A site walkover of the field study site at Holme Dune Nature Reserve was carried out on 12th March 2010. This also included a meeting with a warden of the Nature Reserve to confirm the feasibility of the study with the Norfolk Wildlife Trust, the managers of the site. The walkover comprised an inspection of the River Hun by walking along the banks to determine any potential problems and health and safety risks associated with the work. In addition to this, potential launch and recovery points for a small boat, which was used to transport and emplace the fibre optic cable, were also identified. A discussion regarding the migratory or nesting patterns of birds and the potential risks to wildlife was also undertaken to ensure minimal disturbance to the existing environment.

2.3 Emplacement and Configuration of the DTS

The main component of the DTS system is the fibre optic cable, this was laid on the bed of the River Hun by using a small (~10ft) rigid hulled inflatable boat to float and transport the cable downstream and subsequently reel off the fibre optic cable from the cable drum and into the middle of the channel where it subsequently was expected to settle onto the river bed due to the cable's weight (which is considerable due to the protective metal sheathing). The cable was also expected to become buried by natural sedimentation processes during the course of the field study.

The control unit/base station was attached to the fibre optic cable in a remote location in close proximity to the most easterly part of the River and nearby a sluice gate (Photographs 1a and 1b). It was partially hidden to minimise the potential of vandalism or interference by the general public which have access to a nearby track as part of the Nature Reserve. The unit was powered by two leisure batteries, fully charged prior to commencement of the field study, which were recharged by a solar panel and a wind turbine, the addition of these energy generators was expected to vastly increase the longevity of the DTS system in the field. The DTS system had not been set-up in such a way previously; therefore the study would also be a test of the reliability of the new power supply set-up. Prior to emplacement the leisure batteries were fully charged.

The Oryx DTS system was configured to obtain a double ended measurement, meaning the light signal would be travelling approximately 4000 metres, comprising both forward and reverse signals over the 2000 m test section of the River. Temperature readings were taken every 15 minutes; with an integration time of 30 seconds for both the forward and reverse signal. This configuration is expected to provide a temperature resolution of approximately 0.05 °C according to performance specifications provided by Sensonet (Figure 4). The spatial resolution was set as high as possible, with measurements taken every 1.01m along the length of the cable. The system was set-up on 30th April 2010 and the data utilised in the study was taken between the date of set-up and 13th May 2010, providing just under two weeks worth of data. This data set was deemed adequate time to monitor any potential responses to groundwater recharge events in the form of groundwater discharge (whether diffuse or discrete), provide control over short-term meteorological variability and allow identification of any other physical processes related to the River Hun hydrological system.

2.4 Follow-Up Site Visits

Site visits to inspect the system and download data from the Oryx's finite memory were carried out on 4th, 7th, 13th, May 2010. An additional visit to conduct 'spot' temperature probing was carried out on 2nd June 2010.

2.5 Calibration of the DTS System

Calibration of the DTS data is important as the system can be affected by small internal temperature increases during operation of the system which can cause increases in temperature of the fibre optic cable with distance from the Base Station. Whilst the DTS system base station contains an auto calibration feature, to allow an external calibration test against a known temperature, calibration ice baths were established at either end of the 'test' section of the River. These ice baths consisted of a small amount (~10 m) of coiled cable inside insulated boxes filled with several kilograms of ice cubes. A TinyTag temperature probe and data logger were emplaced in each calibration ice bath and set to measure temperature at 1 minute intervals for several days.

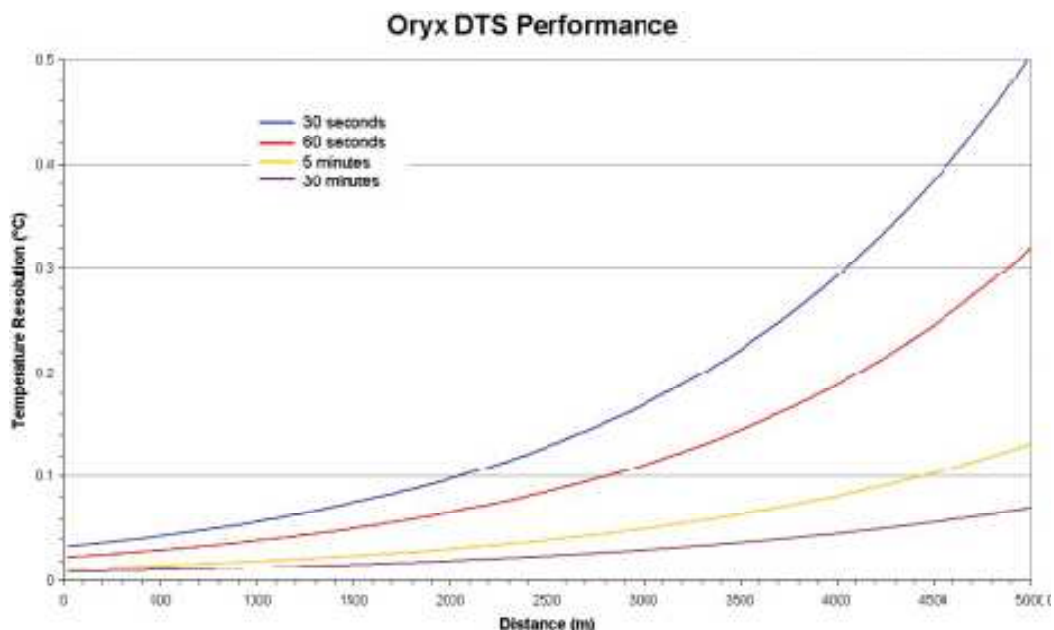


Figure 4 - Oryx DTS Performance (Sensornet, 2010) – Forward and reverse signal travels 4000 m, providing temporal resolution of approximately 0.05 °C.

Of main import to the calibration is the recording of the lowest temperature and the time span it was recorded over. The calibration ice baths both maintained a recorded temperature of -0.6 °C between 0844 hrs on 08/05/10 and 0944 hrs on 09/05/10. Due to the length and stability of this data set it was deemed acceptable to use for calibration. Simultaneously, the DTS recorded minimum temperatures of -0.16 °C and 2.63 °C at the base station

(Ice Bath 1) and the end of the test section, (Ice Bath 2), respectively. This temperature difference between identical calibration baths has led to the conclusion that Ice Bath 2 may not have been set-up in the correct manner. Consequently, data from Ice Bath 2 has not been used for calibration of the DTS data.

The difference between Ice Bath 1 and the associated Tiny Tag probe varies between 1.52 °C and 3.61 °C, with an average difference of 2.79 °C (Figure 5). This is the calibration error of the instrument and has been subtracted from the DTS data set. Increased accuracy of monitoring may have been attained had a longer integration time for forward and reverse signals been utilised in the configuration of the Oryx DTS system. However, this may have caused much of the short term variation to be lost. All of the following Excel graphical representations utilise the calibrated DTS data. Unfortunately the MATLAB plots (Figures 12 and 13) do not.

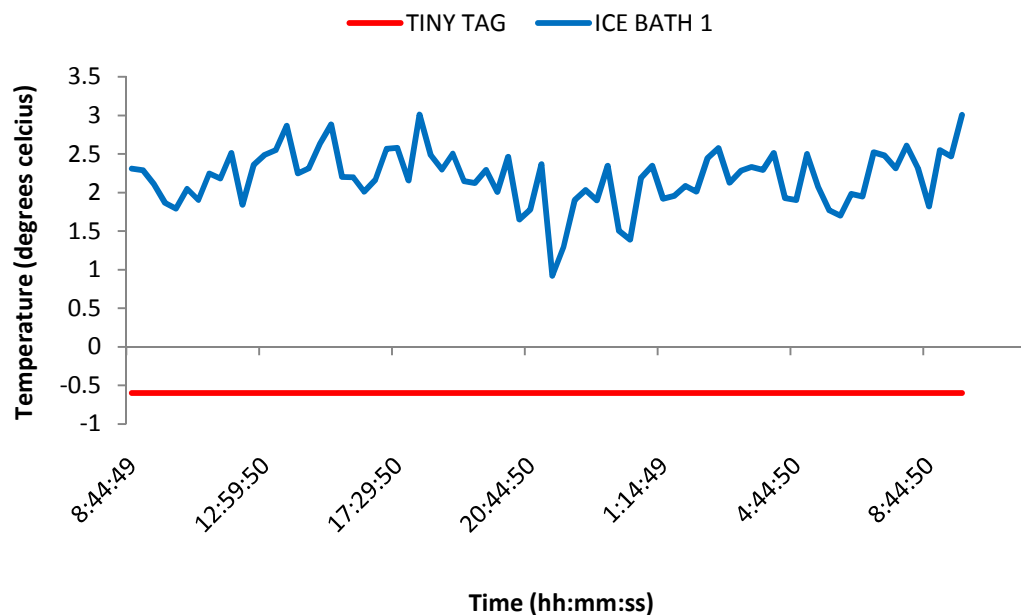


Figure 5 – Calibration data from DTS and Tinytag

The relatively high calibration error of 2.79 can be attributed to having only a small length (<10m) of coiled cable within the calibration bath used. This short calibration section was used as a result of the ice bath being set-up after emplacement of the DTS cable and is considered to produce a calibration error that is neither accurate nor representative of the DTS system. Ideally the calibration ice bath should contain a longer length of cable, Tyler *et al.* (2009) suggest 30 m or more maintained at a constant temperature is preferential to determine the calibration error of the system. Regardless, the error has still been applied to the Excel data to obtain a more representative temperature than otherwise produced by the DTS system.

3. RESULTS AND DISCUSSION

3.1 Introduction

The data analysis has been carried out using simple statistical analyses and visual identification of relative temperature anomalies through graphical representation of data using MATLAB or Microsoft Excel software packages. The MATLAB scripts were kindly provided by Dr Victor Bense, the Project Supervisor, and are appended. These scripts allow the MATLAB software to read the .ddf files created by the Oryx DTS system and produce an accurate visual representation of spatial and raw (i.e. non-calibrated) temporal temperature data. The set-up of the Oryx DTS system was expected to provide an accuracy of 0.05 °C for the recorded .ddf files according to Sensornet specifications. The Excel software programme cannot directly read the .ddf files, thus a database was required to create graphical representations of the data to support the analysis. The database created is composed of data from the forward signal or first 'half' of the double-ended measurements, as such some accuracy may be lost as the double-ended measurements are forward and back averaged. However, as the study aims to identify relative temperature anomalies within the data set this is not considered to pose a significant issue to the analysis.

3.2 DTS System Performance

As discussed previously, Sensornet specifications for the Oryx DTS suggest that monitoring at a spatial resolution of 1 m is achievable. However, Tyler *et al.* (2009) claim that some manufacturer's specifications can be somewhat misleading and go on to suggest that spatial resolution may vary by as much as 3 m in some cable-instrument combinations. The study also suggests that spatial resolution is a function of the integration time of the measurement. Following the methodology adopted by Tyler *et al.* (2009) both spatial resolution and temporal repeatability of the DTS are assessed by use of the recorded field data and the results discussed.

3.2.1 Spatial Resolution

Tyler *et al.* (2009) define spatial resolution as "the length of fibre required to show 90% of the known temperature change". Where the temperature change is calculated as the difference between the average River water temperature (T_{river}) and the temperature within Ice Bath 1 (T_{cal}), both recorded by the DTS. This is carried out for a specific time series interval over a length of cable recording a step change in temperature. It is recommended that to achieve an

accurate and representative result the test should be carried out for 60 time intervals. However, for this study, only one time interval is assessed in order to provide a rough estimation of the potential variability in spatial resolution. The particular time series interval analysed was chosen on the basis that it provided the most stable temperature range immediately before and immediately after the step temperature change, thus providing the most representative 'base' temperatures (T_{river} and T_{cal}). A spatial resolution of 5.50 m is calculated for this particular time series. This is much greater than the quoted spatial resolution stated by the supplier of the DTS system. However, this may be due to the accuracy of the spatial resolution test and calibration data rather than the accuracy of the Oryx DTS system.

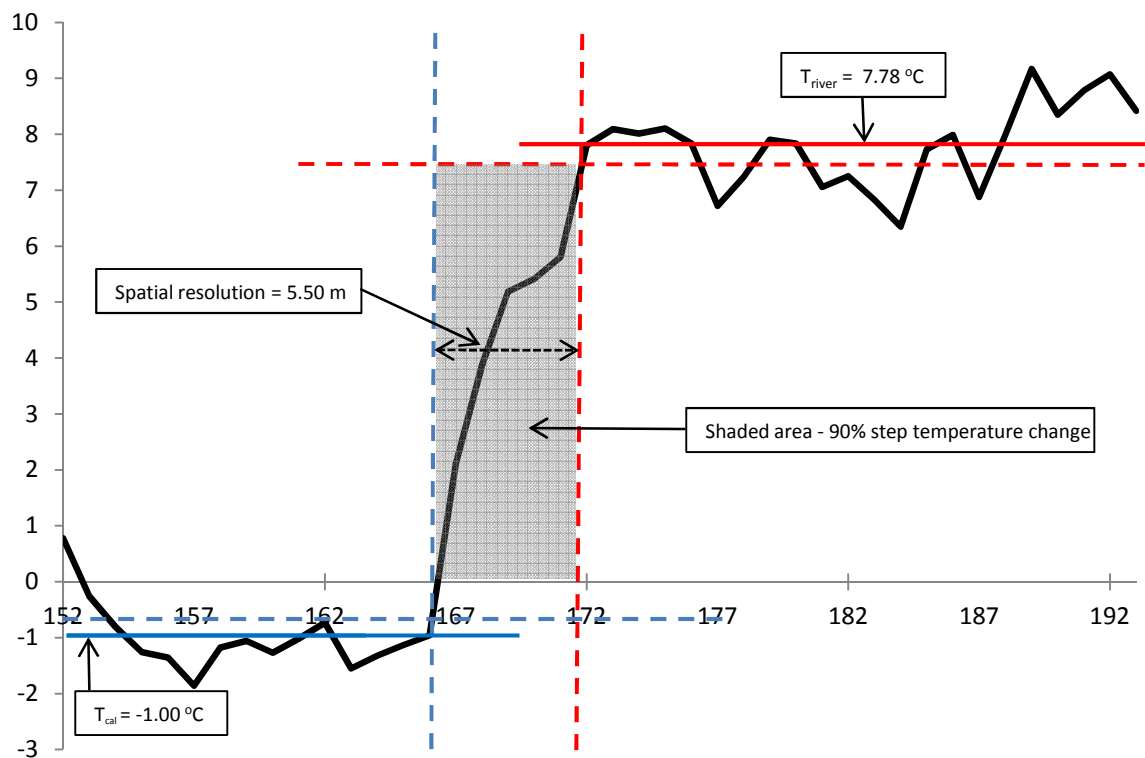


Figure 6 - Illustration of the spatial resolution calculation for a single time series interval (08/05/10 – 1029 hrs)

Increasing the accuracy of the spatial resolution estimation can be accomplished by using greater lengths of cable maintained at a constant temperature either side of the temperature step change. Tyler *et al.* (2009) suggest a minimum length of 10 times the spatial-averaging interval of the DTS system being tested (i.e. at least 10 m).

3.2.2 Temporal Repeatability

Temporal repeatability can be considered an important limiting factor in the accuracy of long-term field studies utilising a DTS system (Tyler *et al.*, 2009). The data analysis carried out for this study relies upon a relatively long time series dataset, the assessment of this allows conclusions to be formulated about the River Hun hydrological system. Temporal repeatability (including instrument drift) can be assessed by monitoring a section of fibre optic cable maintained at a constant temperature, in this case the calibration ice bath held at -0.60°C , whilst the DTS is exposed to the environmental stress of temperature change associated with the field study. Figure 5 displays the calibration data, temporal standard deviation of this data produces a result of 0.37°C . Considering the poor quality calibration of data (caused by the short length of cable in the calibration bath) and the relatively lengthy timescale over which the calibration took place (~ 24 hours) this result can be considered good. In fact Tyler *et al.* (2009) suggest that multi-day experiments can produce instrument drift in the region of ± 1 or 2°C , further enhancing the credibility of the precision of the DTS system.

3.3 Groundwater Discharge to River

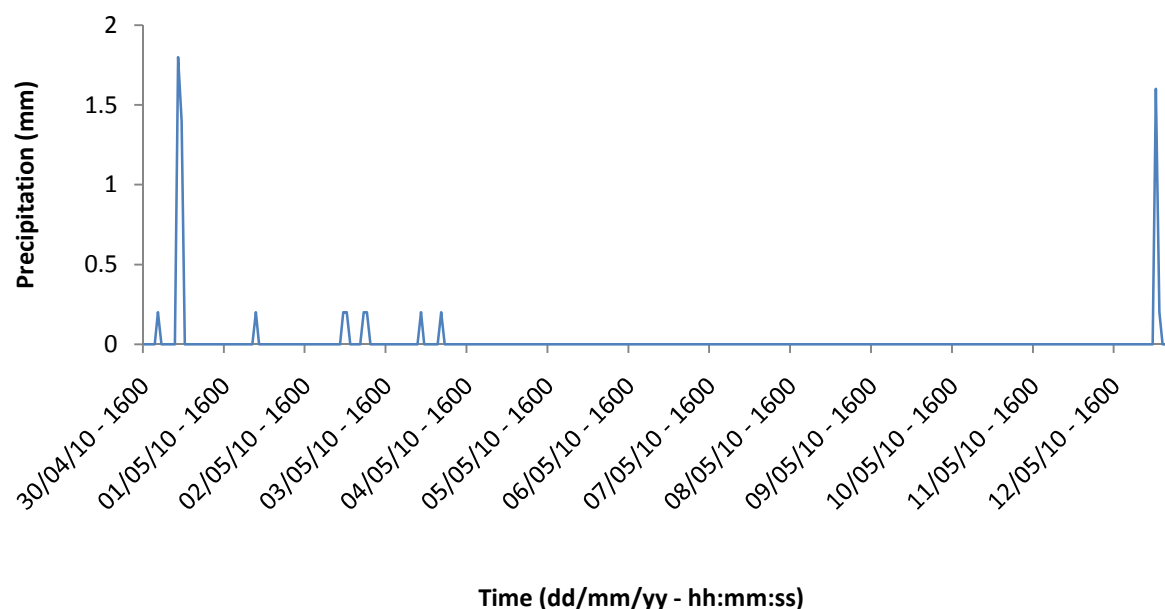


Figure 7 – Hourly precipitation data from Hunstanton weather station, approximately 7 miles south-west of the field study site (kindly provided by King's Lynn and West Norfolk Council)

The term to describe groundwater discharge to rivers is baseflow. This input is usually quite stable as it is representative of slowly changing groundwater levels in the local aquifer.

However, discharge can sometimes show a rapid response through recharge by precipitation (Ward and Robinson, 2000) via the process of 'piston displacement', first identified by Smith *et al.* (1970).

The field study was carried out over a period of approximately two weeks. This length of time was deemed sufficient to record any significant groundwater discharge events which may occur. It was hoped that a storm event with large amounts of rainfall would lead to easier identification of groundwater discharge zones in the River Hun. However, from analysis of Figure 7 above, it becomes apparent that very little precipitation and thus subsequent recharge of the groundwater system occurred during the period of study. A maximum of 1.8 mm per hour precipitation was recorded between 0100 and 0200 on 01/04/10. Consequently, very little recharge driven groundwater discharge into the River Hun is expected to have occurred during the field study. However, this does not have any direct implications on the study as background levels of groundwater discharge into the River Hun are unknown. Additionally, the precipitation is not considered to have significant impact upon surface water temperatures in the river.

Data recorded between 1200 hrs on 07/05/10 and 1300 hrs on 10/05/10 is considered anomalous, this is discussed in more detail in section 3.4.2 below.

3.4 Data Analysis

3.4.1 Introduction

The Oryx DTS system recorded 960 data files over a little less than two weeks. The temporal resolution was set for 15 minute intervals, thus it can be seen that the data retrieval was not wholly successful. Figure 7, below, graphically illustrates the diurnal variation in recorded river temperatures. Larger gaps in data retrieval are easily identifiable and are highlighted below, the most noticeable are found between 2345hrs on the 1st to 0330hrs on the 2nd and 1145hrs on the 7th to 0845hrs on the 8th of April 2010. These breaks in the data record are thought to have occurred due to a loss of power and subsequent recharge either by the solar panel or the wind turbine connected to the control unit which were installed to minimise such problems. Also, it should be noted that the system has sporadically recorded at 30 minute intervals and also very rarely at 60 minute intervals. The reason for this irregular monitoring is unknown.

3.4.2 Diurnal Variations

The variation in minimum and maximum temperatures, exhibited in Figure 7, is considered to be representative of daily variation in atmospheric temperature (including longwave radiation) and solar radiation caused by local meteorological conditions. When compared together, as in Figure 8 below, it becomes clear that atmospheric temperature and river temperature are intrinsically linked. This is intuitive and of course is to be expected where the River is not significantly overgrown or influenced by external factors. Considering the climate throughout the study period, the River water is expected to generally have a higher temperature than air as water is a better retainer of heat than the atmosphere. However, minor temporal displacements in diurnal maximum and minimum atmospheric-river temperatures are also observed in Figure 8. This is considered to be caused by local meteorological variations, differences in monitoring techniques and the environmental parameter being monitored which have differing physical characteristics and associated thermal properties.

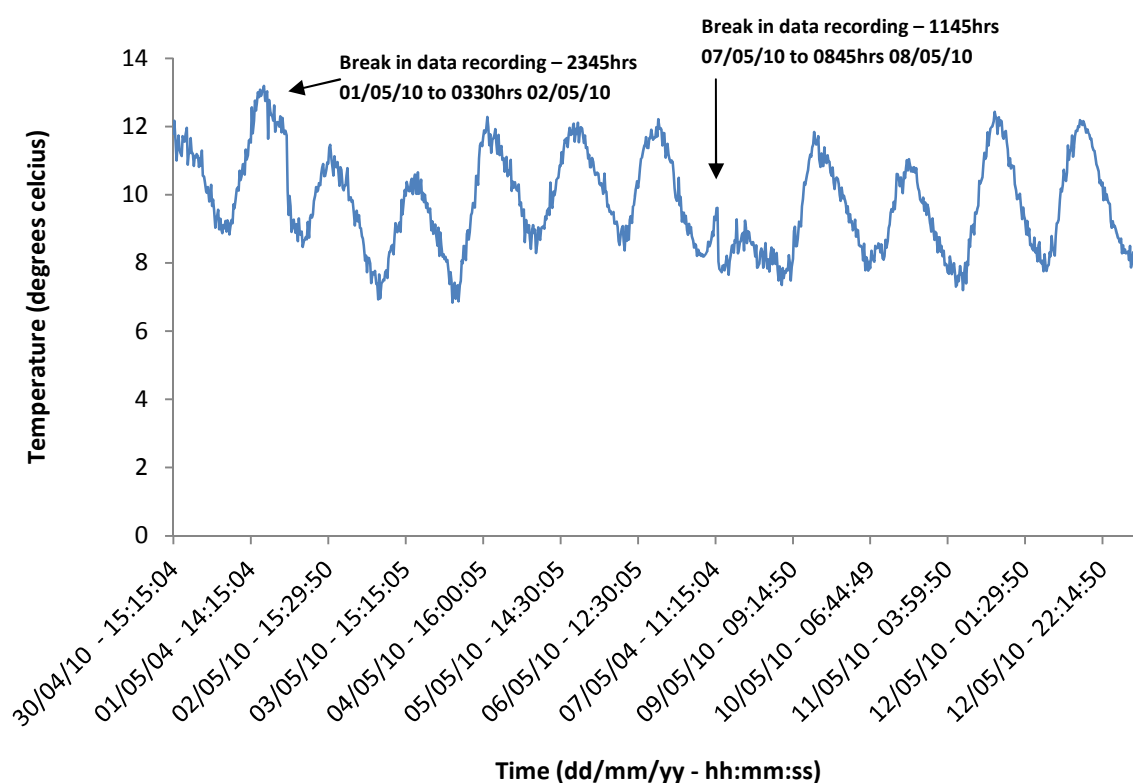


Figure 7 – Average temperature (°C) plotted against daily time (hh:mm:ss)

Anomalous atmospheric temperature data is exhibited between 1200 hrs on 07/05/10 and 1300 hrs on 10/05/10, a value of 10.70 °C was recorded for the duration of this period (Figure 8). It is suspected that the weather station was offline for this period of time.

Coincidentally, this break in recording starts near simultaneously, approximately within 15 minutes, of the largest break in the data set recorded by the DTS. Due to this anomalous atmospheric temperature recording the precipitation data for the same time span is also considered anomalous.

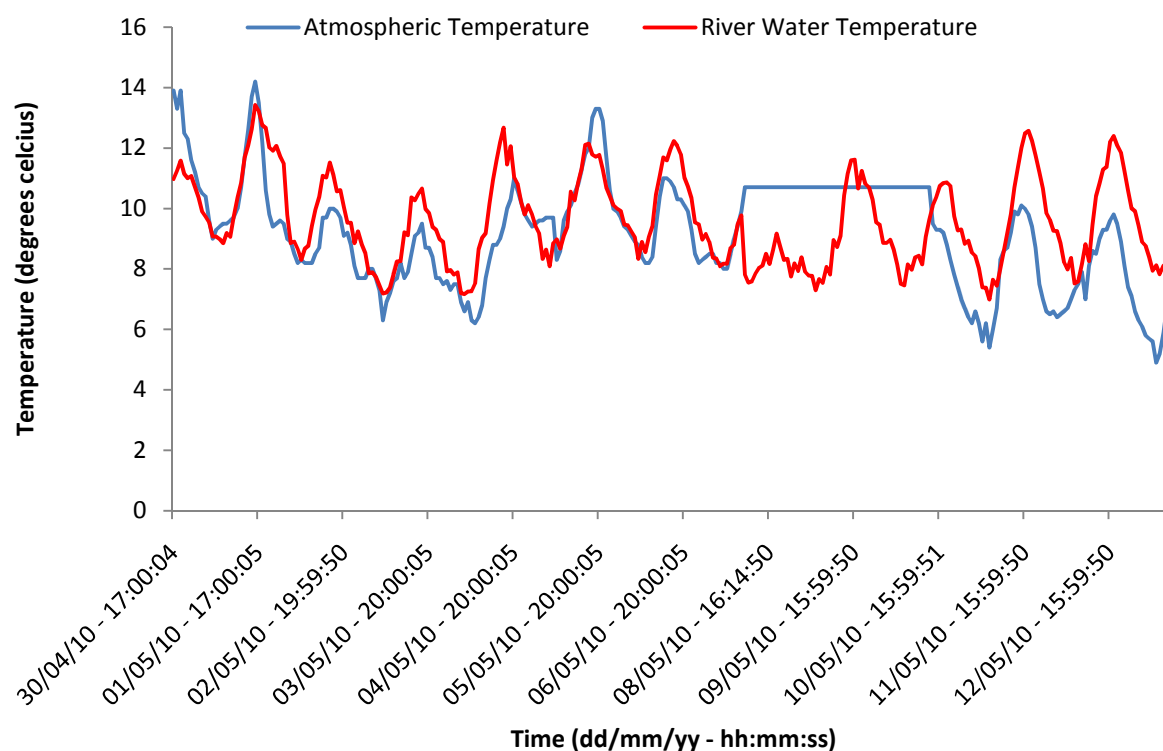


Figure 8 – Hourly average atmospheric and river temperatures

Diurnal variations in standard deviation are also evident within the recordings of the DTS data set. These variations range between 0.24 °C and 0.75 °C with an average standard deviation of 0.48 °C (Figure 9). Particularly low standard deviations were identified between 0645 hrs and 1015 hrs on 07/05/10, unfortunately this period of time coincides with a gap in meteorological data, and for the last two days of the field study on 12/05/10 and 13/05/10, which remain anomalous as only large amounts of precipitation are considered to cause such moderated temperature readings. Meteorological data does not record such occurrences. Peaks in standard deviation are considered to be caused by greater variations in water temperature during the day brought about by increased solar and longwave radiative warming of preferential areas of River physically open to such influences and cooler areas within shaded areas.

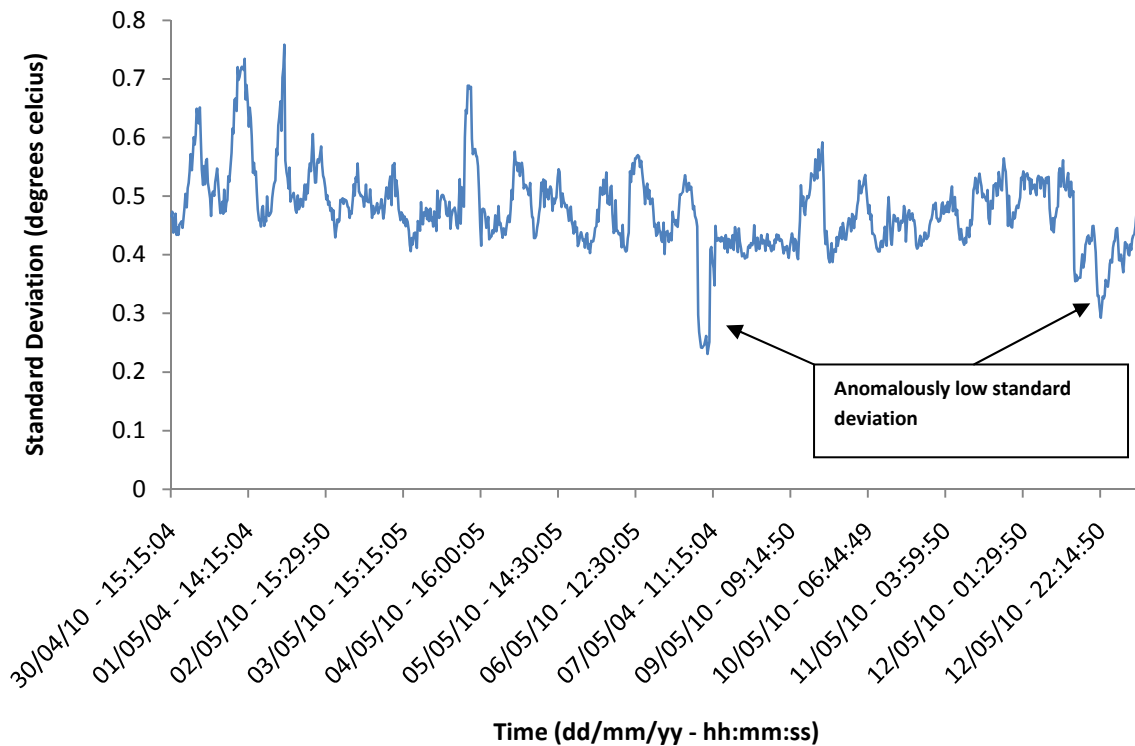


Figure 9 –Standard deviation ($^{\circ}\text{C}$) of diurnal temperature variations (hh:mm:ss)

3.4.3 Spatial Variations

Figure 10a, below, a plot of average river temperature against distance along the fibre optic cable/River Hun test section, highlights the spatial variation in river temperatures. Much of the ‘see-saw’ variation can be attributed to the variation in emplacement of the fibre optic cable in the river and noise from the monitoring instrument.

An example of how variations in emplacement of the cable can affect the data is clearly illustrated by the area 1600 m and 1800 m of the test section where average temperatures were found to be approximately 0.2°C higher with an average standard deviation 0.19°C lower. Initially, these moderate temperatures appeared to be representative of groundwater inflow. However, upon closer inspection it was found that the fibre optic cable had become well buried ($\sim 20\text{ cm}$) in the river bed. The sediment surrounding the fibre optic cable was considered to act as an insulator during colder periods and a conductor of heat during warmer, sunnier, periods, thus acting as a moderator to the DTS signal. Between 1600 m and 1800 m the River was also found to be straighter, wider, shallower and clearer of vegetation than most other localities throughout the test section, allowing more sunlight to reach the river bed and subsequently warm the fibre optic cable.

A reduction in river water temperature with increasing distance from the base station (0 m) to the end of the test section at about 2000 m is evident in Figure 10a, with the difference reaching approximately 0.5 °C from beginning to end. The difference in temperature is considered to be representative of the physical characteristics of the River Hun surface water system and not indicative of warmer groundwater inflow. Nearer the base station the river was found to be anthropogenically altered to be wider, straighter, deeper and incorporates inflow from both drainage ditches and shallow surface water bodies, or 'ponds', which collect from/on the adjacent farmland and discharge directly into the river either through direct connections at a confluence or via overflow pipes. The drainage ditches and surface water bodies receive very little inflow from fresher, cooler water, except during periods of rainfall, and contain what can be considered to be near stagnant water. Consequently, when these water bodies are subjected to warming by solar radiation they achieve and maintain a greater temperature than the adjacent River Hun.

Temperature probing was carried out to investigate the possibility of a natural hydrological pathway (i.e. ignoring the overflow pipe) between the 'ponds' and the nearby River Hun. Probing was carried out within the largest of these 'ponds' at approximately 1000 m and at the closest edge of the River (Figure 9), with probing of the bed carried out at 0.5 m depth. The probing found that the 'ponds' contained warm water with the bed temperature at 0.5 m depth recorded at 19.8 °C and water in the overflow pipe to the River at 19.6 °C. Upstream of the potential 'pond' – River Hun linkage the bed temperature was found to be 14.4 °C. Where the overflow pipe discharges to the River the bed temperature was found to be 13.8 °C and 5 m downstream, 13.6 °C. Downstream a further 5 m, 10 m and 21 m the bed temperatures were found to be 15.2 °C, 16.1 °C and 14.9 °C, respectively. These increased bed temperatures are considered to be caused by diffuse inflow of warmer water contained within the adjacent 'pond' of shallow warm water.

The implication of this on the study seems to be that inflow from surface water bodies will mix with the River Hun and cause the temperature of the River to increase further downstream. This increase can clearly be seen in Figure 10a, with an overall downstream increase in temperature in the region of 0.5 °C. In the context of the aims of the study, these warmer inflows are problematic as they will mask cooler groundwater inflows whether they are diffuse or discrete.



Photograph 2 – Shallow surface water body or 'pond' adjacent to River Hun (out of shot to right of photograph).

It is hypothesised that stable inflows from warmer surface water will produce a lower variability in the data set which will be reflected by lower standard deviations. Spatial correlations exist between peaks in temperature and troughs in standard deviation, Figures 10a and 10b (red dashed line). Several of these anomalies also roughly correlate with locations of drainage ditches and a possible outflow pipe location (620 m) along the River Hun test section (Figure 9) (red dash 1-4 at 620 m, 880 m, 1060 m and 1470 m). This supports the hypothesis which suggested that surface water bodies are the cause of the general temperature increase downstream (or nearer to 0 m) identified by the DTS system.



Figure 9 – River Hun test section and surface water drainage

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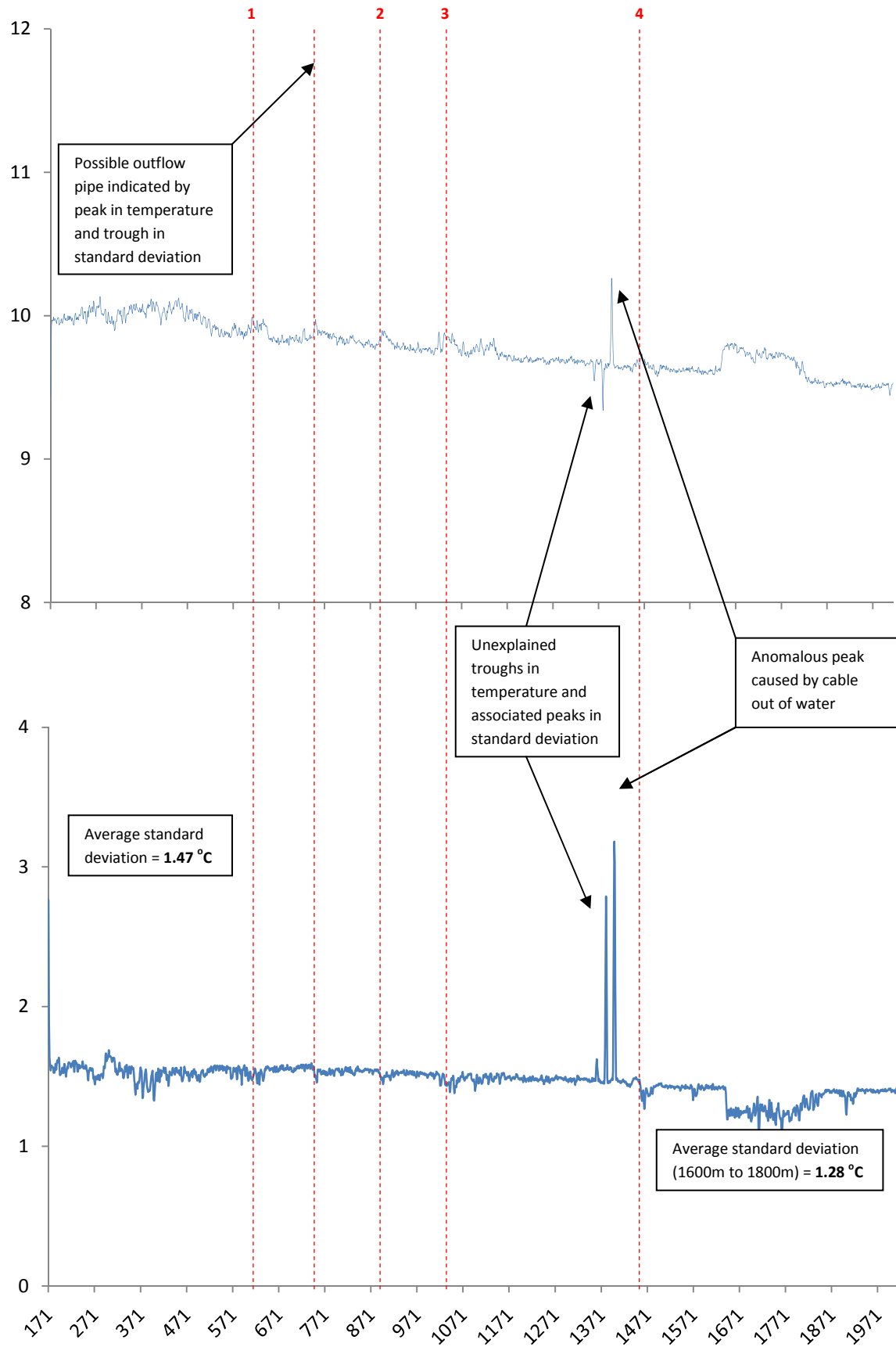


Figure 10a and 10b – Temperature (°C) (Top) and Standard Deviation (°C) (Bottom) against Distance (m)

Another distinguishing feature of Figures 10a and 10b is the general reduction in standard deviation with distance from the river mouth, this somewhat mirrors the temperature reduction, and is also considered to be caused by the change in the physical characteristics of the River system. Particularly as farther upstream there are fewer tributaries from drainage ditches which act to variably increase the temperature and subsequently the standard deviation.

3.5 Tidal Incursion

The tidal data (Figure 11) has been kindly supplied by the British Oceanographic Data Centre (BODC) for the Port of Cromer in North Norfolk, the tide times are thought to differ to those of the study site by approximately +30-40 mins. The data encompasses a spring-neap-spring cycle with spring tides at the beginning and end of the study.

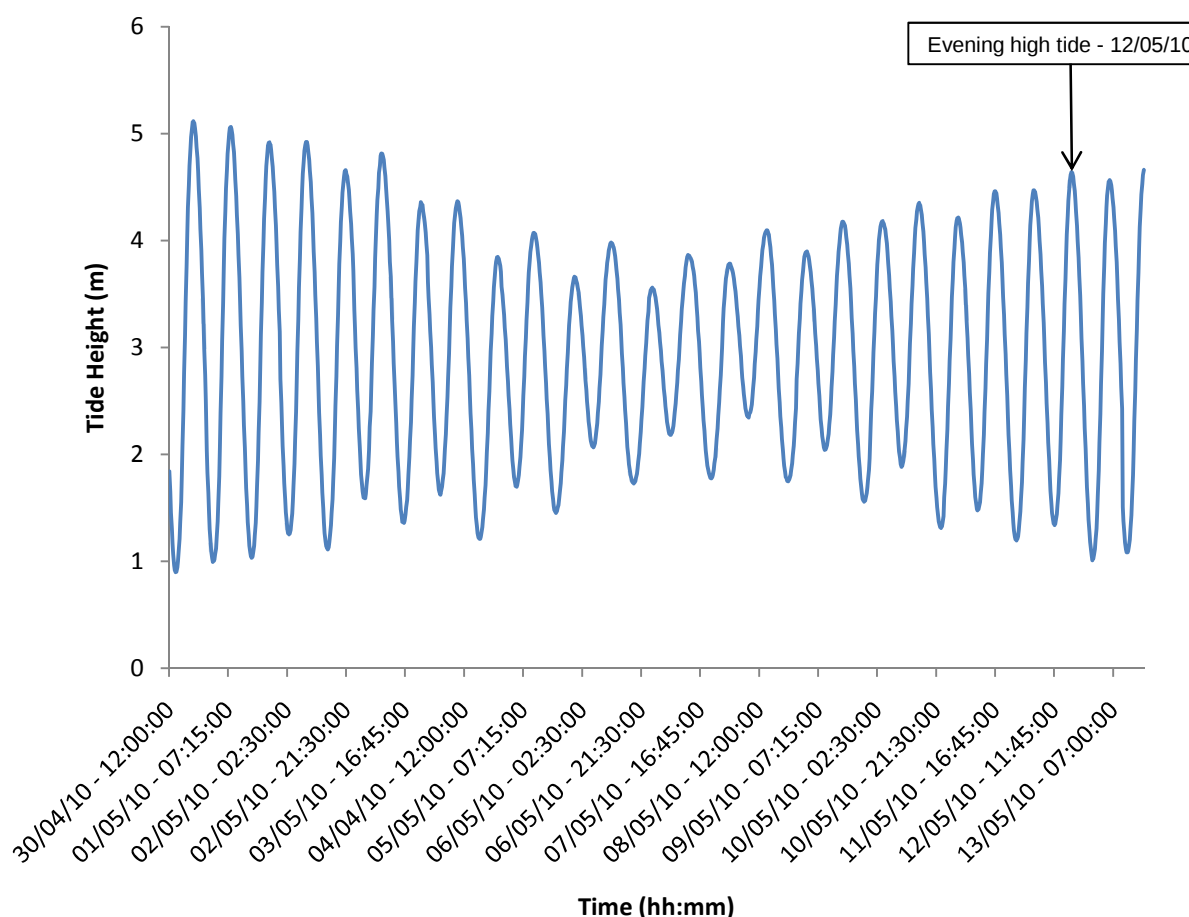


Figure 11 – Tide chart from Port of Cromer, approximately 30 miles to the East, for period 1200hrs 30/04/10 to 1745hrs 13/05/10.

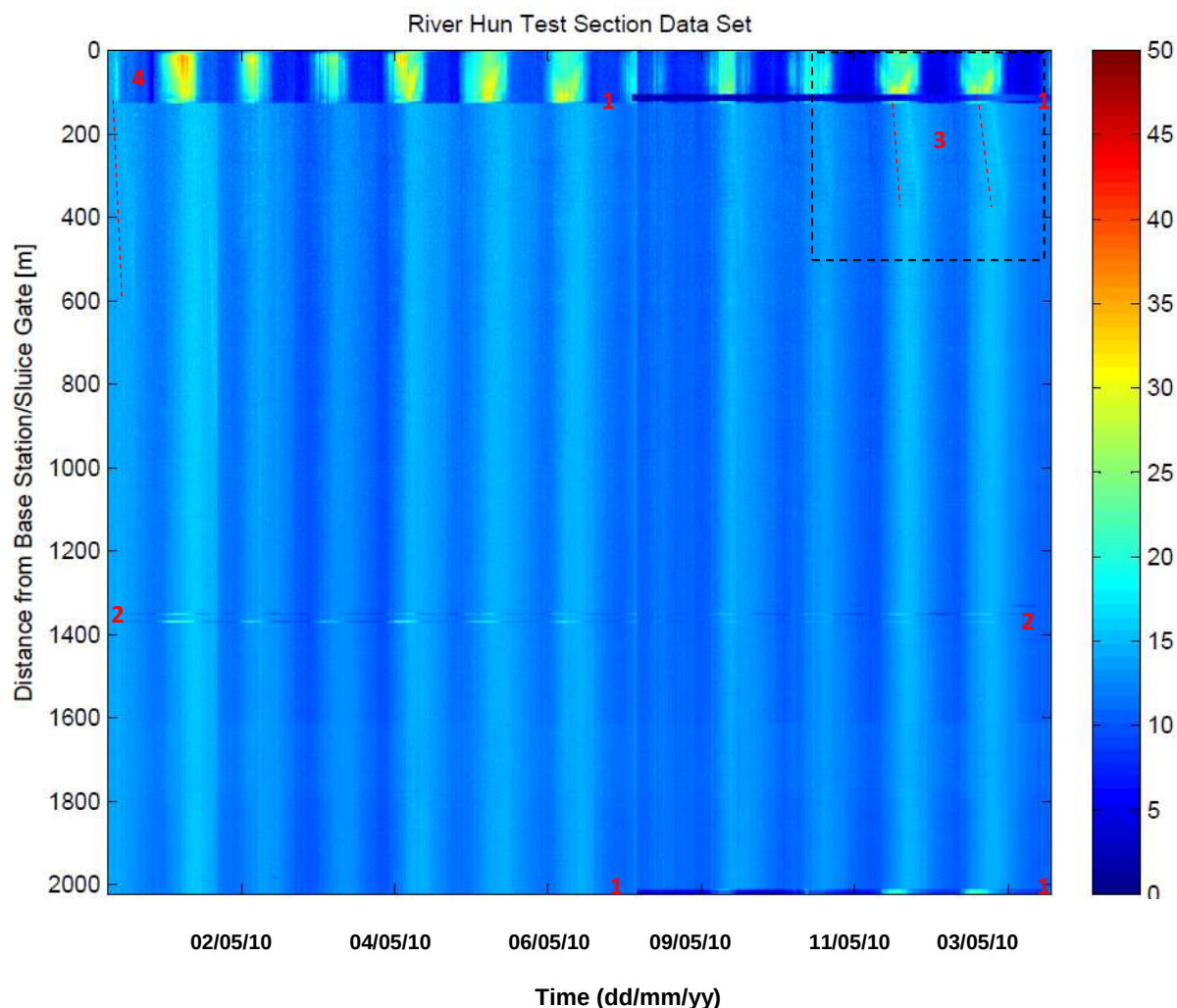
Anecdotal evidence provided by a Holme Dune National Nature Reserve warden suggested that during high tides on the spring cycle a nearby 'top hat' cover for a borehole overflowed with groundwater, exhibiting free flowing artesian groundwater conditions. Unfortunately no data was available for this borehole and it is understood that no monitoring takes place. This evidence is contrary to the popular understanding that groundwater discharge at a sea-land boundaries occurs at mean sea level elevation. Several studies of tidal wave propagation into aquifers (Turner *et al.*, 1996, Jeng *et al.*, 2002, Vandenbohede and Lebbe, 2007) suggest that increases in amplitude can occur as a result of differential, and more importantly, preferential flow directions caused by the alignment of grains composing the nearshore sediments. Of course it should be noted that amplitude and propagation of the tidal wave within the aquifer are functions of tidal amplitude, storativity and transmissivity of the aquifer, mean sea level, leakiness of the aquifer and tidal speed.

Another possible explanation for this discharge of groundwater is that as the tide rises on the spring peaks a raising of the piezometric head occurs due to an increase in vertical stresses, brought about by the extra weight of the seawater, and subsequent reduction in porosity in the underlying aquifer brought about by compaction. However, this theoretical hypothesis relies upon the underlying lithology being re-compactable such as a fibrous peat might be. The modern deposits of peat and clay bands may provide this condition and are considered to be the predominant near surface soils underlying the field study site.

The DTS system temperature recordings indicate an increase in river temperature up to 350 m upstream of the sluice gate (Figures 12 and 13). By comparison with the tidal data it can be seen that these temperature increases correlate with peaks in the spring cycle at the end of the field study. The temperature increases are considered to be induced by tidal incursion through the sluice gate at the River mouth. Unfortunately, only limited data is available for this tidal incursion and none for the temperature of the seawater mixing with the surface water body. However, it is inferred that the seawater is warmed during the rising of the tide over the mudflats which dominate the area beyond the sluice gate and that the tidal range is of sufficient magnitude to, in fact, mix upstream with the River. It should be made clear that this is not expected to show similar behaviour to that of a tidal bore, but more likely gently mixing upstream with the River water. However, the limit of the incursion is expected to be controlled by the same processes which control tidal bore dynamics where the extremity of the bore is found to be a function of water depth, tidal magnitude and river discharge.

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Key to Figure 12 –

- 1** Cool temperatures represent calibration ice baths
 - 2** Increased maximum and minimum temperatures represent atmospheric temperature where the DTS fibre optic cable is out of the water
 - 3** Warmer colours to the right of the dashed red line represent tidal incursion of warmer water
 - 4** 0 to approximately 100 m, fibre optic cable remaining on cable reel adjacent to base station
- Dashed box represents Figure 13, expanded on next page

The MATLAB presentation of the data (Figures 12 and 13) does not include the calibration error of 2.79 °C applied to the data utilised in the production of the other graphical illustrations (from Excel). However, this is deemed to be insignificant given that it is relative temperature anomalies that are under study. Diurnal variations in temperature are exhibited in Figure 12 by the change from warmer to cooler colours and vice versa. The higher temperatures recorded at the beginning and end of the study are a reflection of the predominant meteorological conditions.

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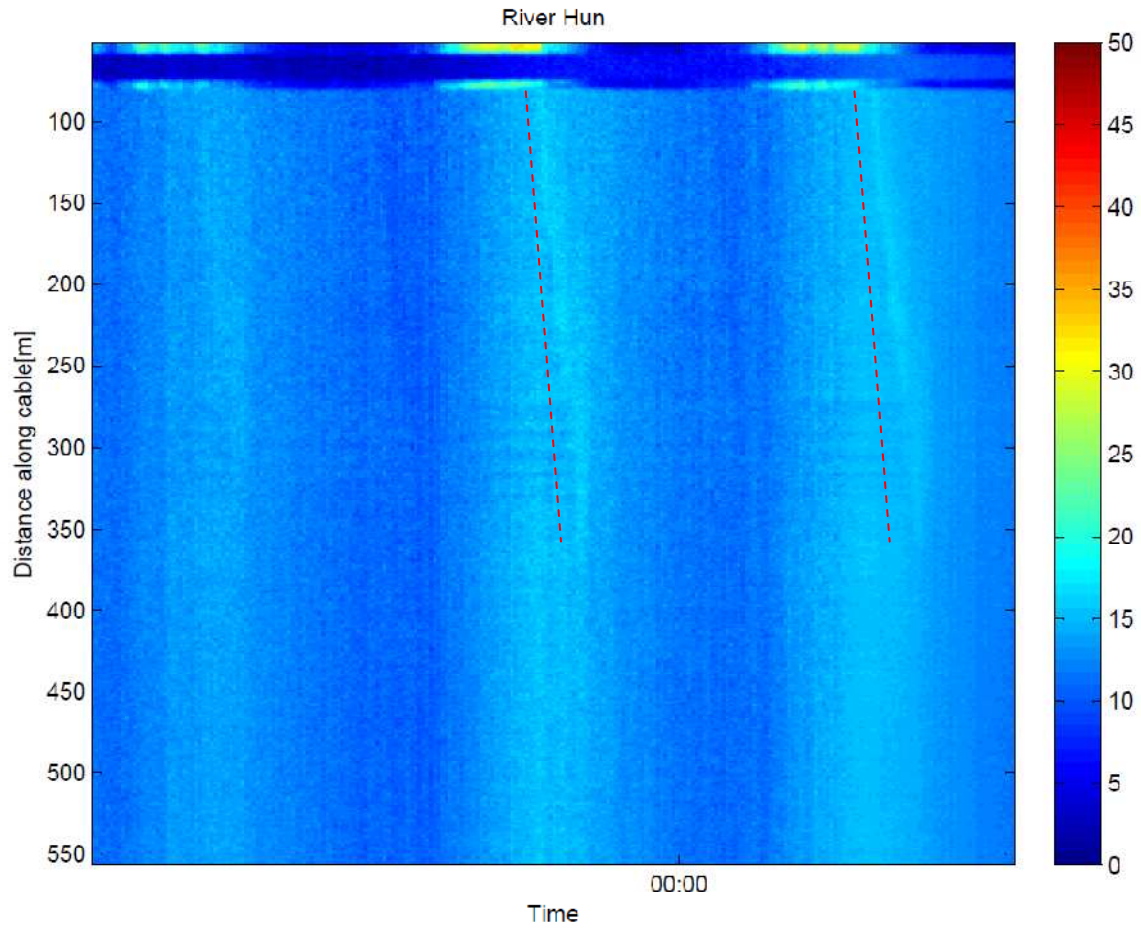


Figure 13 – An expanded area of Figure 12. Temperature increases are evident to the right of the dashed red lines and indicated by relatively warmer colour than surrounds.

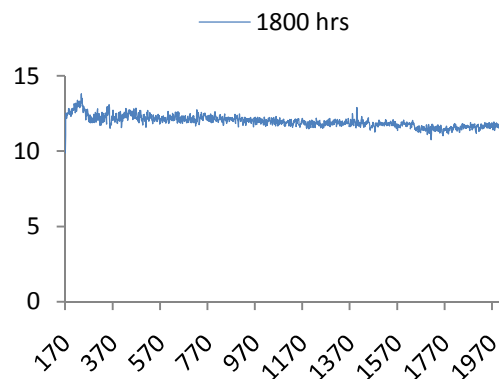


Figure 14a

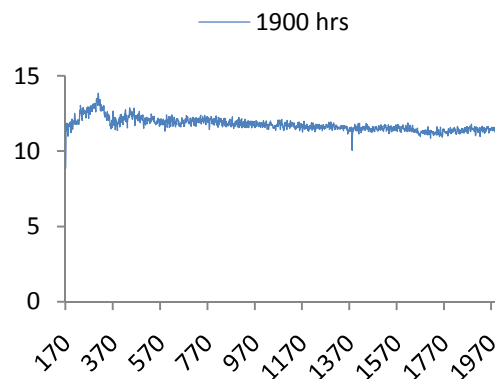


Figure 14b

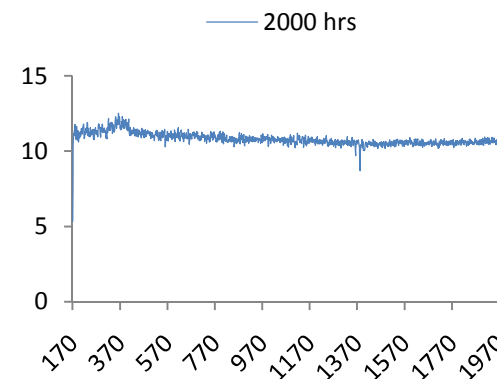


Figure 14c

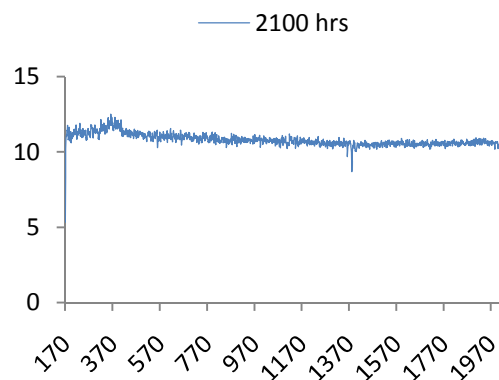


Figure 14d

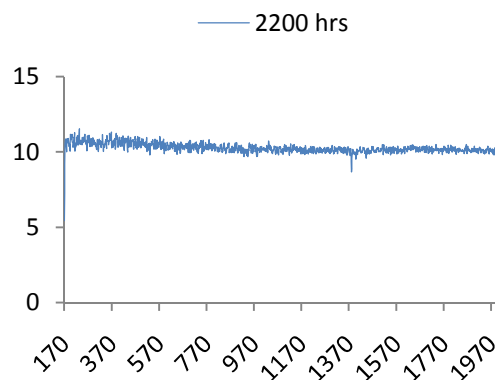


Figure 14e

Figures 14a to 14e:

Temperature (°C) vs distance (m) (12/05/10)

A temperature peak at ~200 m is visible at 1800 hrs (14a) and can be seen to move upstream (14b to 14d) to ~350 m before diminishing by 2200 hrs (14e). This progressive peak corresponds to the temperature increases indicated on Figures 12 and 13 and are considered to be caused by tidal incursion.

Figures 14a to 14e depict the advancement of the tidal incursion upstream from the sluice gate with peaks in temperature representing the tidal component. Initially, anomalously low temperature readings are evident at ~170 m along the fibre optic cable, this represents a small amount of fibre optic cable which was still attached to the cable reel, located upon the River bank and adjacent to the DTS base station and subject to atmospheric temperature changes. The peak at approximately 200 m, which is considered to be very close to the sluice gate end (within 50 m), is first evident at approximately 1800 hrs on 12/05/10, coinciding with the rising of the spring tide on the same evening (Figure 12). This peak can then be seen to laterally shift upstream to approximately 350 m before disappearing by 2200 hrs. Several other similar tidal incursions occur during spring high tides but these are of less magnitude than that which are illustrated by Figures 14a to 14e. Alternatively, the time series can be plotted together as in Figure 15 below. Also of note is the abrupt reduction in temperature found in all time series at approximately 350 m to 360 m. An average temperature of 12.56 °C with standard deviation of 0.44 °C corresponds to the section 182 m to 357 m. This is in contrast with an average temperature of 12.24 °C and standard deviation of 0.25 °C for the section 357 m to 782 m. The reduction in standard deviation is considered to be significant and indicative of the upper limit to which the tidal incursion propagates during this tidal cycle.

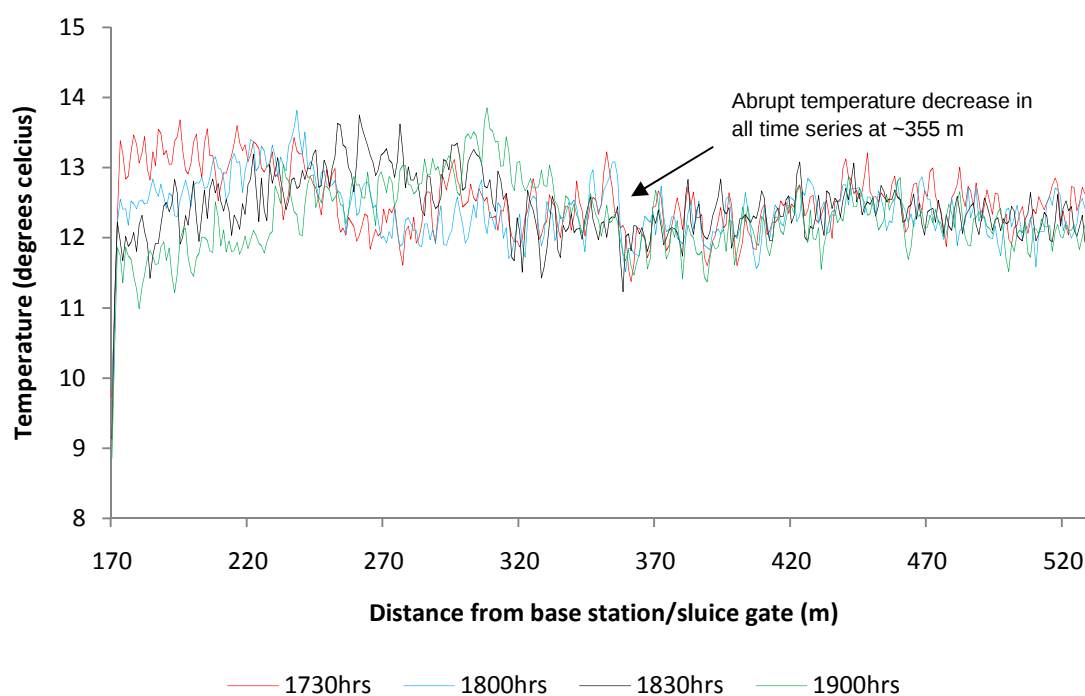


Figure 15 – Multiple time series of temperature plotted against distance, indicating upstream tidal incursion of warmer water.

3.6 Assumptions and Limitations of the Study

The small diameter and low thermal inertia of the fibre optic cable means that the DTS is expected to respond well to variations in water temperature and not be affected by longwave or solar radiation during the day. The spatial resolution test suggests that the DTS system did not record as accurately as was expected, perhaps by as much as 5 times less resolution. Although, calibration data suggests quite a good temporal repeatability was achieved.

During the site visits to download data from the Oryx's finite memory, inspect the DTS system and carry out temperature probing it was noticed that the fibre optic cable had not settled onto the bed in a multitude of places due to obstructive vegetation or debris, and was in fact out of the river in one location (~1370 m) due to a large build up of un-penetrable debris. Throughout the majority of the test section the cable was found to be suspended in the River, between a few centimetres above the river bed and a few centimetres below the surface of the water. This was not deemed to be completely prohibitive to the study as River water temperatures would still be recorded and may still indicate relative temperature anomalies. However, this problem meant that significant groundwater inflows would have to occur in order to be identified by the DTS. The only location where the cable was found to have settled properly onto the bed and subsequently buried was between 1600 m and 1800 m. This was deemed to be the major limiting factor of the projects main objective of enabling identification of groundwater inflow, as much of the groundwater is expected to have become mixed with River water before being monitored by the DTS system.

Unfortunately, no information on the existing local groundwater regime was available for the study, an environmental consultancy in association with the Environment Agency was contacted with regards to obtaining details of nearby boreholes and controls on the sluice gate, however, after several emails and telephone calls no information was forthcoming.

Additionally, only minor amounts of precipitation were recorded over the monitoring period, suggesting that minimal amounts of groundwater recharge took place and that a lowering of the groundwater level probably occurred over the monitoring period rather than any significant groundwater discharge to the River.

4. CONCLUSIONS

The Sensornet Oryx distributed temperature sensing system was deployed by floating the cable downstream in a boat and reeling off the cable and allowing it to settle onto the River bed. Although this method was relatively easy, fast and useful for areas where there is a lot of surrounding vegetation, it was found to be only partially successful as although the DTS recorded a very rich spatial and temporal data set, the lack of a secure emplacement of the fibre optic cable upon the bed of the river meant that river water temperatures recorded by the DTS were somewhat moderated. Consequently identification of groundwater discharge zones was made difficult. Inferences of groundwater discharge zones could be made where variability exists, however this would rely upon many assumptions and not be scientifically factual. Similar studies to this presented by Selker *et al.* (2006b) and Lowry *et al.* (2007) found significant, and easily identifiable temperature differences, therefore it is the belief of this author that the variation contained within the data set may have been larger than any differences between groundwater and River water temperatures. Access to nearby boreholes would have improved the study by enabling a background recording of groundwater temperatures thus allowing clearer delineation between River water and groundwater temperatures. Additionally, the time of year for the study may not have been best chosen as identification of the groundwater inflow signal is more easily made where greater temperature differences exist between River and groundwater. This is usually during the winter when groundwater is much warmer than surface water bodies.

Separation of groundwater and River water temperature signals is further complicated by the existence of streambed heterogeneity. Where groundwater inflows are present in the River system further variability will be created in the data set by heterogeneity associated with streambed sediments and their intrinsically related hydraulic conductivity. Separating these two variables is consequently made difficult where emplacement of the cable is not 'standardised' i.e. physically buried to a specific depth. Thus, only groundwater inflows of significant magnitude are expected to be recognised. As discussed previously, significant groundwater discharge to the River is not expected to occur as very little groundwater recharge took place during the field study. Hence, the lack of identification of groundwater inflow may be caused by the lack of groundwater inflow into the River system.

Nevertheless, the data set recorded by the Oryx DTS system provided a scientifically interesting and environmentally useful study. Several features of the River Hun system were able to be identified, such as the drainage ditches and the inflow from nearby surface water bodies (or ‘ponds’) identified by the warmer inflows and reduced standard deviation. Tidal incursions were also identified by migration of relatively warm temperatures from the sluice gate end of the ‘test’ section to approximately 350 m upstream.

Recommendations to improve the study include re-emplacement of the fibre optic cable, utilising ‘pegs’ to attach the cable to the River bed. Thus obtaining more representative temperature recordings of potential groundwater inflows. Spot temperature probing can subsequently be used to further investigate areas which are provisionally identified by the DTS system to corroborate the data and determine the nature of the inflow whether it be diffuse or discrete. Shallow soil sampling could also be carried out to determine the immediate underlying geology, this would provide a greater understanding of stream bed heterogeneity and allow closer inspection of potential groundwater discharge zones. Carrying out stream flow measurements by use of flow meters could also be carried out to enable quantification of groundwater discharge through application of energy balance theory over the same test section, after Selker *et al.* (2006b).

$$Q_i^j \times T_i^j + Q_g^j \times T_g^j = Q_o^j \times T_o^j \quad \text{Eq. 1}$$

where stream flow is Q , temperature is T , at time j . Water entering the test section (inflow) has subscript i , and outflow, o . Groundwater discharge has subscript g . Considering conservation of mass, $Q_o^j = Q_i^j + Q_g^j$, the ratio of Q_i^j and Q_g^j is:

$$\frac{Q_i^j}{Q_g^j} = \frac{T_o^j - T_g^j}{T_i^j - T_o^j} \quad \text{Eq. 2}$$

Therefore if the temperature of groundwater discharge, T_g , is known, the stream outflow from the test section, Q_o , can be equated from:

$$Q_o = Q_i \times \left(\frac{T_g - T_i}{T_g - T_o} \right) \quad \text{Eq. 3}$$

Subsequently, the difference between inflow and outflow of the test section can be attributed to groundwater discharge. However for this study the test section over which this is carried out would have to be reduced to exclude external inputs such as the drainage ditches and outflow pipes into the 'test' section. It is suggested that testing this methodology might be most pertinent for the area 0 m to 500 m where there are expected to be no external surface water inputs to the system. It is also suggested that lines of best fit are used to project temperatures across the test section (Selker *et al.*, 2006a), as spatial variability of temperature in the River Maisbach, where the study was carried out, was found to be large (over 1 °C difference through a cross section). Similar variability was found in the study of the River Hun, although the cause may be the poor emplacement of the fibre optic cable and poor spatial resolution of the DTS system. Regardless, the DTS can provide a much greater spatial resolution than traditional point measurement techniques allowing the energy balance method to be applied. Although the study failed to identify groundwater inflows it is still considered a success as the DTS system identified several inputs into the River Hun system, proving its worth as an environmental monitoring system. The findings of the study indicate that the DTS system can be reliably employed to find temperature anomalies within hydrological systems. The system is considered to be of low impact and could have several applications for ecological studies. For example, understanding of the hydrological system is of import to biological classification, this is particularly relevant for this study as upstream tidal incursion was found occur. This influx of salty seawater may have implications on the ecology of the system and may require tighter controls as fresh water habitats may be in jeopardy during the spring high tide cycle. Alternatively, the DTS system may also be a useful tool in river monitoring programmes where effluent discharge is of concern and traditional monitoring techniques cannot be applied. A similar application to this was proven successful by Hoes *et al.* (2009) who identified illicit discharges to sewers through use of DTS technology.

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APPENDIX

Basis of the MATLAB script provided by Dr Victor Bense (Supervisor) including a few basic amendments carried out by Author.

```
clear all

files = dir('*.ddf');

%cable length

x=[0:1.01:2002*1.01];

time_start=[2010 04 30 16 30 00];
time_start_1=[2010 05 13 12 00 00];
time_start=datetime(time_start);
time_start_1=datetime(time_start_1);
dt=time_start_1-time_start;
t=time_start:dt:time_start--length(files)*dt; %time since start of the
experiment (

%reserve space
T_c1=NaN(length(files),2002);
figure
for i=1:length(files)
file_t=char(files(i,1).name);
T_c1(i,:)=dlmread(file_t, '\t', [761 1 2762 1]);
plot(0:2001,T_c1(i,:))
title(file_t);
ylim([-2 35]);
ylabel('Temperature(degrees celcius)')
xlim([0 2000]);
xlabel ('Distance (m)')
drawnow
%fclose('all')
end

%plot a subset

figure
imagesc(t,x,T_c1');
caxis([0 50])
colorbar;
xlabel('Time')
ylabel('Distance from Base Station/Sluice Gate [m]')
title('River Hun Test Section Data Set');
```